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Individual Differences in Finger Reactions

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INDIVIDUAL DIFFERENCES IN FINGER REACTIONS

Introduction

The purpose of this experiment has been to investigate the speed and accuracy of the reactions of the fingers of the two hands in response to visual stimuli. Many suggestions have been put forth from time to time, offering explanations for the lack of regularity between the action of the various fingers when applied to piano playing. These are for the most part mere observations, or at best unscientific reports. A little volume by Grabill[1] and one by Eckhardt[2] are two of the few studies that really attack the fundamentals underlying control and adjustment of the members used in piano playing.

Since piano playing is to a large degree dependent on the proper control of speed, energy and accuracy in finger movement, it seemed important to investigate the relationship between time and accuracy, leaving the more involved factor of energy to subsequent experimentation. Piano teachers have been content to go blindly on, using the hit-and-miss method, or where there has been developed a more or less successful method, it has never been reduced to such objective terms that the teacher may say to the student, "We know this because it has been experimentally demonstrated."

If one can experimentally show that some fingers are inherently slower and less accurate in their responses than others, then exercises for the development of particular fingers may be devised and used to advantage. If these fingers be the same for each individual, the process is simpler. However, if these fingers be found different according to the individual, the method may still be

[1] Grabill, E. W., "The Mechanics of Piano Technique, " Chicago, 1909.

[2] Eckhardt, Robt., "Piano Exercises for the Development of Side-Finger Action and the Development of an Equal and Maximum Spread between the Fingers," Columbus, 1899.

employed, providing the individual differences can be determined before the student begins his work.

It seems desirous to investigate not only the individual finger differences, but also the various combinations and reactions that involve more than one finger. Briefly stated, the investigations reported in this paper fall under the following heads:

1. The relation between speed and accuracy of the individual fingers.

2. The relation between speed and accuracy of the various finger combinations, both when responding with one finger at a time and with two at a time.

3. The relation between the speed and accuracy of the left and right hands.

4. The relation in speed and accuracy between two-finger and one-finger responses.

5. The relation in speed and accuracy between two-hand and one-hand reactions.

6. The differences between individuals on the basis of speed and accuracy.

7. The effect of practise.

Historical

The history of the study of reaction times dates back to the time when the astronomers first attempted to measure the personal equation in transit obervations. Sanford[3] records that Maskelyne, the British Astronomer Royal, first noticed that his records differed from those of his assistant by 1/2 second. The astronomer reported that the assistant had been in this error for some time before he noticed it and that he did not seem likely to get over it. He supposed that the assistant had fallen into some irregular and confused method of observation instead of using the "excellent (Bradley) method." The assistant was accordingly discharged. For twenty years after this incident no mention was made of individual differences. In 1816 von Lineman mentioned it and then it fell under the eye of Bessel, who in 1822 published

[3] Sanford, E. C., "Personal Equation," Am. Jour. of Psychology, v. 2, pp. 1-38.

the results of the first tests that showed individual differences in recording the times of steller transits.

All of this early work was done by the "eye and ear" method. When the star is about to make its transit, the observer reads off from his clock, and then he watches the star in the telescope, and continues to count the second beats. He fixes firmly in mind, as the moving image approaches the wire, its place at the last beat before it crosses the wire and its place at the first beat after. From the distances of these two points from the wire, he estimates by eye the time when the star crossed in tenths of a second. "The role of the mind in observations by this method," says Sanford, "is the fixing of the exact place of the star at the first beat, the holding of the same in memory, the fixing of the place at the second beat, the comparison of the two, and the expression of the relation in tenths." It was not until 1850 that the chronograph was first used to record the time at which a star crossed the meridian. This is the first recorded example of reacting with a key to a visual stimulus.

In the same year (1850) Helmholtz published the results of the first simple reaction time experiments. This was the beginning of the psychological period and the purpose of the most of these experiments was to determine the speed of nervous conduction. After determining the speed of conduction in the motor nerve of the frog to be 27 meters per second, Helmholtz measured the physiological time (in man) which elapsed between the stimulation by a weak stimulus and the execution of the movement. He found the total time ranged from 125 to 200 sigmas, the first reaction times published. This was followed by experiments on the part of many investigators, each trying to establish the rate of conduction of the nervous impulse. The results of most of the experiments differed and Du Bois Reymond in 1900 showed that the differences found were all probably due to too small numbers of subjects and trials and to faulty technique.

The first experimental work done from a psychological interest was that done by Donders and deJaager, published in

1865. Henmon[4] classifies the various phases of the problem of reaction time into three groups:

1. Time relations of simple and complex mental processes and their variations with the quality, intensity and complexity of stimuli. (Occupying center of interest from 1865 to about 1888.)

2. The effect of direction of attention on reaction times. (1888-1905.)

3. The introspective analysis of the reaction. (1905-19—.)

The emphasis or ascendency of the several phases of the main problem has shifted from time to time and at present experimentation covers all the aspects of the problem. It seems wholly unnecessary in a study of this kind, to give a detailed bibliography of the general subject of reaction time. Such a bibliography has been compiled by recent writers on the subject.[5] Reference will be made to such articles as have a particular bearing or interest in connection with the subject at hand.

Donders and deJaager were among the first to show that the difficulties in the study of reaction time were due to the complexity of the problem, the kind of stimulus, the mode of reaction, the degree of attention, and many other factors would alter the results. They also decided that the reaction time method was impracticable as a means of determining the rate of nervous impulse. At about this time the physiologists ceased to be interested in the problem, so that experimental work on reaction time came to be carried on largely by the psychologists. Donders and de Jaager, followed by others, adopted the use of reaction times as a method of determining or measuring more complex processes, notably discrimination and choice.

The earliest recorded experiments using the two hands is that of Donders.[6] If one stimulus appeared the subject was to react with the left hand, if the other appeared the subject was to react

[4] Henmon, V. A. C., "The Psychological Researches of J. McKeen Cattell," Archiv. of Psych. No. 30, April, 1914.

[5] Wells, G. R., Psych. Rev. Monog. v. 15, No. 5, 1913.
Moore, T. V., Psych. Rev. Monog. v. 6, No. 1, 1904.
Salow, Paul, Psychologische Studien, Bd. 7, 1912.

[6] Donders, Arch. f. Anat. u. Physiol. 1868.

with the right hand. He assumed that this involved discrimination and choice, and that by subtracting from these results the results of simple reaction times, the time for discrimination and choice would be established. The study does not bear directly on the problem of finger or hand differences, however. This problem received little attention during the earlier years of the experimental work on reaction times.

Wundt[7] in the first study that appears in the Philosophische Studien emphasized the importance of studies in time measurements in psychological research and from the beginning, it was a subject of research in the Leipzig laboratory. Nor has the importance of this field of investigation ceased to be pointed out. Watson[8] emphasizes the importance of experimentation on conditioned reflexes and reaction times. His attitude differs from that of Wundt, Titchener and others. Watson's interest leans strongly towards the physiological. Cattell expresses a similar attitude on the importance of this field, an attitude that has dominated his work, "these sciences (i.e. physiology and psychology) cannot rank coördinate with the physical sciences until they consist of exact measurements."

Although the problem of reaction times has been considered important and has been the subject of investigation for the past quarter century, very little has been done to investigate the relation of symmetrical movements, executed either simultaneously or in insolation. The problem of attention occupies most of the literature on reaction time of this period.[9]

Among the earlier studies was that of Cattell[10] who produced a large number of reactions from each of two subjects, D and C. In the first series an electrical stimulus was applied to the several parts of the arm, in the second series the stimulus was touch.

[7] Wundt, W., "Über Psychologische Methoden," Philosophische Studien, Bd. I.

[8] Watson, J. B., "The Place of the Conditioned Reflex in Psychology," Psych. Rev. v. 23, 1916.

[9] Ach, N., "Über Willenstätigkeit und Denken," Göttigen, 1905.

Woodrow, H., "The Measurement of Attention," Psych. Rev. Mon. v. 17, No. 5, 1914.

[10] Cattell, J. McKeen, "On Reaction Time," Memoirs Nat. Acad. Science, v. 7, 1893.

The chief purpose of these experiments was to measure the speed of nervous impulse, but the experimenters decided that the results did not warrant any conclusions in regard to specific rate of nervous impulse, in fact that the method of reaction time was not a valid one for measuring the speed of the nervous impulse at all.

In a later work, Cattell and Dolley[11] further demonstrated the fact that the reaction time method is impracticable as a method of determining the rate of the nervous impulse. In investigating the problem as to whether the reaction time is shorter when the stimulus is given to the reacting hand than when it is applied to the other hand, they obtained positive results and also concluded that there is no difference in the reaction times of the two hands.

At about the same time (1893), Sanford[12] experimented on the effect of stimulating the reacting hand or the opposite hand, on the reaction time, the obtained results in accord with those of Cattell and Dolley. For electrical stimulation he found that the reaction time was 10 sigmas shorter when the stimulus was given to the reacting hand than when it was given to the opposite hand. He made no direct study of the difference in reaction times between the two hands, but a comparison made on the basis of his tables shows the relative reaction times for the right and left hand, for he, (Sanford) performed his tests with both the right and left hands as the reacting hands. When the stimulus was applied to the reacting hand for:

Subject	S,	R.H.	is faster	than	L.H.
"	B,	R.H.	" slower	"	L.H.
"	R,	R.H.	" slower	"	L.H.

When the stimulus is applied to the opposite hand from the one that reacts, the following is true:

Subject	S,	R. H.	is slower	than	L. H.
"	B,	R. H.	" faster	"	L. H.
"	R,	R. H.	" slower	"	L. H.

[11]Cattell, J. McK., and Dolley, S. C., "On Reaction Times and the Velocity of the Nervous Impulse," Psych. Rev., v. I, No. 2, 1894.

[12] Sanford, E. C., "On Reaction-times when the stimulus is applied to the Reacting Hand," Am. Jour. Psych., v. V, 1893.

His summary table of results is as follows:

TABLE A—Reaction with Right Hand
(after Sanford)

Subject	Stim. in R. H. number reactions	Stim. in R. H. average time	Stim. in R. H. av. var.	Stim. in L. H. number reactions	Stim. in L. H. average time	Stim. in L. H. av. var.
S	10	128.4	8.	10	142.7	9.
B	22	145.8	10.1	21	143.4	6.8
R	11	153.3	6.6	13	150.	6.1

TABLE B—Reaction with Left Hand
(after Sanford)

Subject	number reactions	average time	av. var.	number reactions	average time	av. var.
S	10	141.9	10.9	10	140.2	5.8
B	22	148.2	10.9	24	131.3	8.1
R	19	138.1	10.9	23	136.6	8.6

All times are given in sigmas.

Sanford accordingly concludes that it makes little difference which hand is stimulated and that the one hand is as fast as the other in reacting. It should be remembered however that the experiments which Sanford performed were with electrical cutaneous stimulation only, and it is not safe therefore to infer that these results are likewise true for other stimulation. Moreover the number of reactions is not large enough to be conclusive. An average of ten or twenty trials leaves a great liability of error. These investigations on the effect of stimulating the reacting or the opposite hand were first begun by Exner[13] and it is an attempt to repeat Exner's experiment that Sanford has made here.

Féré,[14] found that the reaction times for the two hands are different, the left being the longer. He also found that the reaction time for the two hands when acting simultaneously is longer than when each reacts separately. The right hand, when reacting alone, has a reaction time of 120 sigmas, when it reacts with the left hand 140 sigmas. The left hand when reacting alone,

[13] Exner, Sigmund, "Experimentelle Untersuchung der einfachsten psychischen Processe," Pflüger's Archives, VII, 1873.

[14] Féré, Ch., "L'energie et la vitesse des mouvements voluntaires," Revue Philosophique, vol. 28, 1889.

has a reaction time of 160 sigmas and when reacting with the right hand 180 sigmas.

He further investigated the effect of warming the hand on the reaction time. He found that after warming the slower hand (the left hand) that the reaction times equalled those of the right hand in speed and in some instances passed them. In giving a record of the effect on the several fingers of the left hand, he gives the reaction times for each finger before the warming process as: thumb, 346 sigmas; index finger, 269 sigmas; middle finger, 266 sigmas; ring finger, 255 sigmas; little finger, 283 sigmas. This very data shows that he found finger differences. Unfortunately he does not publish values for the fingers of the right hand, so that a complete set of values is not accessible from his experiments. He is one of the earliest writers to note the relation of the reaction time problem to the development of technique by the pianist.

Ach[15] in a set of experiments in which the subjects were to react as soon as they recognized the color of the card presented, had the subjects react with the right hand and the left hand on alternating days. His results showed that for subject L, the reaction time for the right hand was 1 sigma longer than for the left hand and for the subject H the reaction time for the right hand was 44 sigmas shorter than for the left hand. In another set of experiments, reported earlier in the same volume, he compares the reaction times for the thumbs and index fingers of the two hands and reports that for subject H the left hand is the faster by 54 sigmas, for subject J the left hand is faster by 56 sigmas and for the subject L it is faster by 2 sigmas.

Probably the most extensive work on the difference between the two hands is that done by Kiesow[16] in the laboratory at Turin. So far as the records show he was the first to investigate the reaction of the separate fingers in a comparative manner. For this set of experiments he was the observer. His results were as follows:

[15] Ach, N., Op. cit., reference footnote 9.

[16] Kiesow, F., "Beobachtungen über die Reaktionzeiten momentaner Schalleindrücke," Arch. f. d. Gesam. Psych., Bd. XVI, 1910, pp. 352-375.

Finger	Right Hand		Left Hand	
	average	mean var.	average	mean var.
1	171.7	19.5	172.4	16.8
2	175.2	17.	178.	13.5
3	166.8	18.5	173.8	13.
4	170.5	16.3	176.2	16.5
5	175.3	19.5	168.7	18.2

Kiesow concludes that the fingers of the right hand give shorter reaction times than those of the left, with the exception of the little finger of the left. He goes on to explain however, that the physiological condition of the little finger of his left hand may not be the same as in other people, due to his long continued practice on the violin. "Durch vieles Klavierspielen habe ich freilich alle meine Finger gleichmäsig geübt, aber ich habe in meiner Jugend auszerdem sehr viel Violine gespielt und hierbei die Bewegungen des linken kleinen Fingers in besonderem Mase üben müssen." In this work he used sound stimuli. He further tried out the difference between the two hands in a set of experiments with four right-handed subjects and three left-handed. The index finger of each hand was used to make the response, and the reaction type[17] he records as motor, i.e, the attention[18] directed towards the muscular reaction. The results were as follows:

Reaction-time of right and left hands to auditory stimuli
(after Kiesow)

Subject	Right Hand		Left Hand		Difference
	Average	M. V.	Average	M. V.	
J.C. (r.h.)	105.3	5.3	109.3	5.5	4.
C.S. (r.h.)	105.2	6.2	109.8	6.4	4.6
L.B. (r.h.)	105.6	5.3	107.6	6.	2.
M.P. (r.h.)	108.	6.9	111.1	6.5	3.1
R. (l.h.)	116.5	8.	107.5	7.	—9.
M.M. (l.h.)	113.4	8.5	110.4	8.6	—3.
P.E. (l.h.)	114.8	8.5	111.6	7.8	—3.2

[17] Salow, Paul. "Untersuchungen zur uni- und bilateral Reaction," Psychologische Studien, Bd. VII, p. 65, ff.

[18] Breitweiser, J. V., "Attention and movement in Reaction Time," Arch. of Psych., no. 18, Aug. 1911.

His results showed that in right-handed people, the right hand is faster and in left-handed people the left hand is faster. In indicating differences in tables, positive values mean right hand faster, minus values mean that the left hand is faster, by the amounts indicated.

Poffenberger[19] found a slight, but what he considered significant, difference in the reaction times of the right and left hands. He gives results from 100 reactions each from two right-handed subjects and 200 reactions from one left-handed subject. He obtained greater differences when only one eye was stimulated, particularly if the eye opposite to the reacting hand was stimulated, but this involves the question of indirect pathways as compared with the direct. This difference he regards as the time lost in conduction in the nerve centers, or the synapse time. His results were as follows:

Reaction-times of Right and Left Hands (Both Eyes Stimulated)
(after Poffenberger)

Subject	Right Hand		Left Hand		Difference
	Average	M.V.	Average	M.V.	
T (r.h.)	184.4	9.9	184.7	5.2	.3
P (l.h.)	160.4	4.4	162.5	5.2	2.1
A (r.h.)	178.9	6.5	177.2	5.	— 1.7

His differences were even smaller than those found by Kiesow. Subject P, who was left-handed, was faster with the right hand by 2.1 sigmas, and subject A, who was right-handed was faster in the left hand by 1.7 sigmas. In T there is no real difference. In fact none of the differences are large enough to be of great significance.

Sinn[20] concluded that the left hand has greater capacity for executing automatic and reflex movements and the right greater for consciously motivated movements. While Sinn does not offer an explanation or further substantiate his point it is in agreement

[19] Poffenberger, A. T., "Reaction-time to Retinal Stimulation," Arch. of Psych., no. 23, 1912.

[20] Sinn, Monatschr. f. Psych. u. Neur., Bd. 26, 1909, S. 234, ff., 321, ff., 430, ff.

with the theory advanced by Meyer[21], namely that during infancy the child is normally left-handed. If this be true, one might expect that the simple reflex movements be faster with the left hand, it being innately the preferred hand. However, the fact which Meyer also points out, that the number of fibres in the sartorious muscle, although greater in the left side in infancy, becomes considerably greater in the right in the adult, rather tends to substantiate a greater possibilty for the right hand in the adult. All experimental work has been done on the adult.

Salow[22] agrees with Sinn in that the left hand has superiority over the right for reflex movements, and he further adds that the left hand reacts at almost its maximum speed from the first, but that the right hand may improve with practise although it will never quite reach the speed of the left. In motor reactions and choice reactions the difference is not significant.

Moore[23] has pointed out the importance of the movement itself. Many investigators in reporting their results have not been careful to state what movements were involved in the reaction. Cattell in his work with Dolley on reaction time as a means of measuring speed of nervous impulse, found that the reaction time is longer when the movement is made from the shoulder, less for the forearm and nearly the same for the wrist and fingers. When a subject is told to press down a key, various sets of muscles may be employed, unless some precautions are used to have the subjects use the same movement. The position of the arm will make some difference and cannot always be entirely controlled. Barnes[24] in his study of reaction with isolation of a muscle group controls more or less satisfactorily the position of the arm and the group of muscles. However this is an artificial condition, one not found in ordinary reactions with which we are concerned, so that there is something to be said on both sides of the question of artificial control of this kind.

[21] Meyer, M. F., "Left-handedness in Infancy," Psych. Bul. vol. 10, 1913, p. 209.

[22] Op. cit. reference footnote 17, p. 80, ff.

[23] Op. cit., reference footnote 5.

[24] Barnes, J. C., "Voluntary Isolation of Control in a Natural Muscle Group" Psych. Rev. Monog., v. 22, no. 1, 1916.

The study made by Barnes is a most interesting one in its relation to piano technique. His experiments deal with the control over special muscles in a group which ordinarily contract together. Most of his discussion and conclusions are based on the introspective data recorded by the observers, but the methods used and the ultimate results are related to the present topic. He found among twenty-two men and ten women subjects no sex differences. He selected the ring finger because it usually has the least independent action of any of the fingers. The experimental performance consisted of moving the ring finger. first in vertical and second in horizontal direction, without movement of the middle and little fingers. The movements of all three fingers were recorded on a drum. At first there were slight movements of the ring finger and many movements of the two adjoining fingers. As the practise increased the movements of the middle and little fingers became less and those of the ring finger wider in amplitude, until perfection in the appointed task was attained. After perfection of the movement by the right hand, the left was given the same experiment. The results showed that when the left hand was placed in the thimbles, the ring finger moved almost as easily and with as great aptitude as though it were continuing the practise of the finger of the right hand, which had been going on for two months. After five trials the movement on the left hand was practically perfect.

The lateral movements of the ring finger are not so important, but a brief summary of results of this group of experiments shows that although the ligaments binding it to the little finger and the middle finger are so arranged that any extensive movement of the ring finger in the lateral direction would always pull one or the other of the two adjacent fingers, nevertheless the movement was learned much more rapidly than movement in the vertical plane. This speed in learning the control of the movement probably was accelerated by the previous experiment, although as Barnes says, it is hardly safe to assert this definitely. For all of the observers the same order was maintained, so that no data is given which offers any information on the relative time of learning for the right and left

hands, when they are the initial performers. In all of his cases the right hand had mastered the movement before the left hand began it.

Practically nothing in the way of research has come from the pianists themselves. It is evident however that some of the best teachers and performers have recognized the problem and the difficulties that it offers to the study of piano technique. Patterson[25] writes thus: "The great secret of beautiful playing on the piano lies in the independent and well regulated touch of each finger on the hand. To acquire this is no easy thing. It may take months and even years of patient practise." The writer goes on to explain that the five fingers of the hand are unequal in size, shape and capability. Their positions in regard to the palm of the hand, as in connection with each other, give to every member of the group an individuality which we emphasize when we speak of the thumb, the index, the middle, the ring and the little fingers. "The pianist, at the commencement of his study, knows how much easier it is to strike a note firmly and clearly with the first and second fingers (usual musical notation of fingers) than with those known as the third and fourth. The reason for this is explained upon examining the tendons of the hand. Both the third and fourth fingers are more fettered by digital ligaments than are the remaining two and the thumb. The hand is constructed rather to grasp or to hold than to strike, in the sense in which we attack ,or touch the keys. Preliminary aids to strengthening the arm muscles, and therefore the hand and wrist action, have been found helpful by many executants."

W. Mason in the same volume[26] in a chapter on the "Two-Finger Exercise" suggests something of the problem of equalizing fingers. Liszt, the great master, says of this two-finger exercise, "There is one little exercise which has come down from Hummel that I never give up. It does one more good than anything else." Lizst is reported to have played it without rhythmical form, just as a gymnastic exercise to increase the

[25] Patterson, A., "Theory of Music and Piano Technique," Encyclopedia, edited by Elson, pp. 193-195.

[26] Mason, W., Op. cit., reference footnote 25, pp. 218, ff.

uniformity of the fingers. Mason suggests other forms of so-called gymnastics for the same purpose, i.e., increasing the uniformity of the fingers. This is the fundamental problem which confronts the pianist in developing technique.

Such indefinite discussions as these are practically all that one finds in the musical literature. Such studies as that of Pond[27] even are not many. His article is one of the few attempts to study music or musical methods from an experimental standpoint. The study is of performance on the French horn, chiefly, and the author points out the value of introspective analysis by a trained observer of the methods of controlling the mouth, lips, breath, and to some degree the fingers. It is to be hoped that many more such studies may follow as aids in developing methods of technique for the various instruments.

Apparatus

The apparatus used for this experiment was that which was designed by Dr. A. P. Weiss for experimental work on conditioned reflexes. It was so nearly like that needed for the present research that Dr. Weiss offered its use and made the necessary modifications. Fig. I shows the electrical connection of the apparatus. It consisted of three parts:

1. The stimulus mechanism (shown in unbroken lines)
2. The reaction mechanism (shown in broken lines)
3. The calibration circuit (shown in dotted lines)

1. *The stimulus mechanism*—The D. C. current entering at point *a*, is passed to the tripper magnet of *A*, which is a horizontal duplex pendulum, so weighted that when the current is passing through the magnet, end *x* of the bar is pulled downward. From tripper magnet A, the current passes to *b*, where it may take one of three branches. The branch *b, l, c* passes through the left signal relay, then through left signal marker and the resistance light 1, to the other terminal of the D. C. socket. In operation this branch gives the left signal and also records it on the paper record strip.

[27] Pond, S. E., "A Contribution to the Study of Instrumental Music," Jour. of Applied Psych., v. II, 1918.

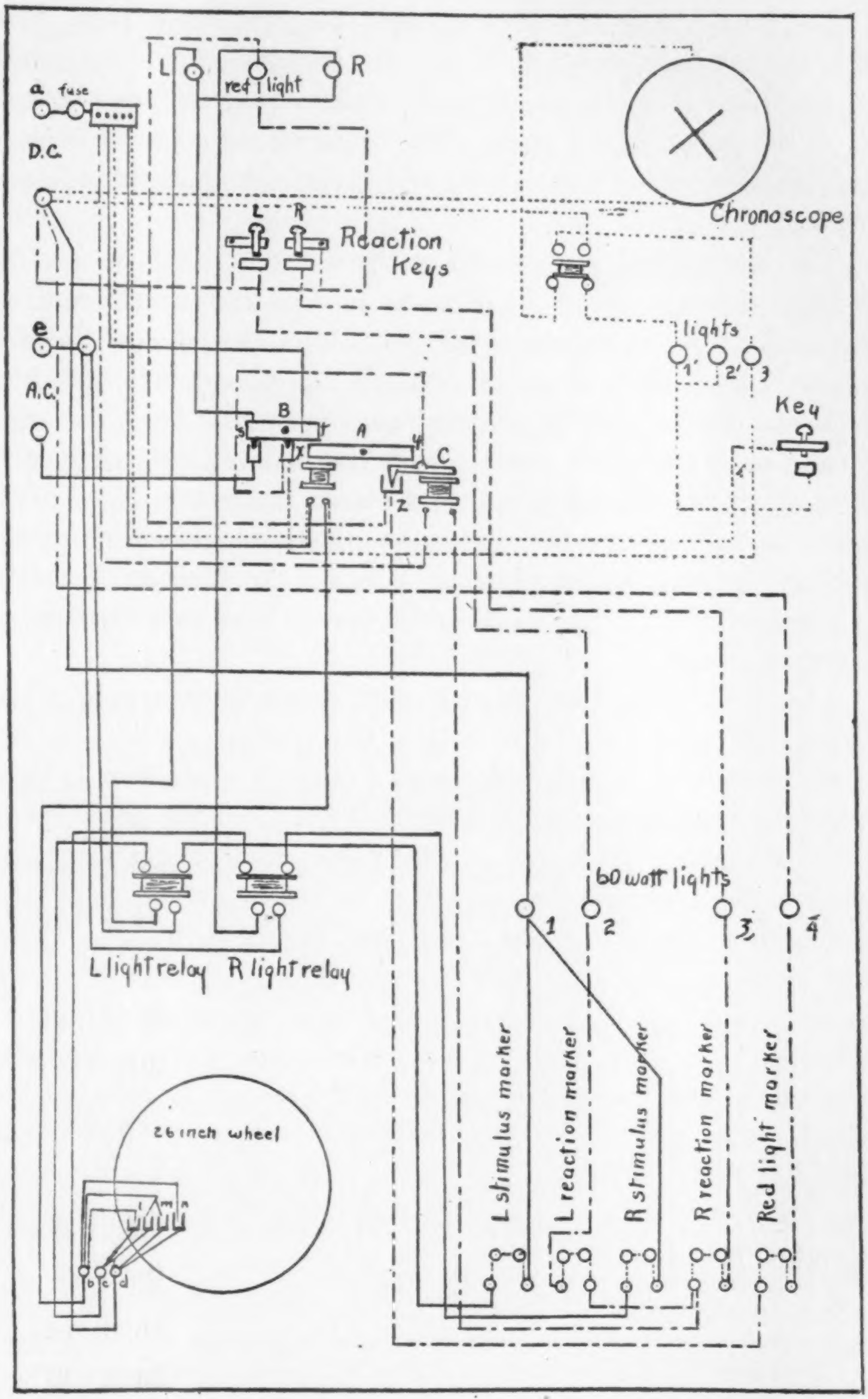


FIG. I.—Diagram of electrical connections for whole of apparatus.

The branch *b, n, d* passes through the right signal relay, then through the right signal marker to the resistance light *1* as above. in operation this branch gives the right signal and also records it on the paper record strip. The branch *b, m, c-d* is merely a combination of both the above and gives a double stimulus and its record.

The large wheel represented in the diagram consists of a flat wooden disc (26 inches in diameter). On this wheel are three rows of screws at varying intervals. Above the edge of the disc are arranged three mercury contacts, *l, m, n.* As the wheel revolves, one or another of these cups is pushed up far enough by the screws to make contact with the hook extending over it. The wheel is revolved by a motor placed under the table. This wheel serves to vary the succession of stimuli presented to the subject and also the time interval between the stimuli. It makes it possible to retain the same order for *each* subject throughout the experiment.

The A. C. current enters at *e,* part going to each light relay. From the right (R) light relay, the current passes to the stimulus light R in the dark room (Fig. V) and from L light relay the current passes to stimulus light L in the dark room. From stimulus light L, the current passes to *B,* the Timer. So long as the *x* end of the tripper *A* is up, the current will pass through the mercury cup at *s* in *B,* and thence outwards. However as soon as the magnet pulls the *x* end of *A* down, then the connection of the A. C. current passing to the stimulus light L is broken at *s.* The object of the break at *s* is to give a stimulus of constant duration independently of the rate of rotation of the wheel. That part of the A. C. current which passes through R light relay to stimulus light R, in the dark room, takes the same path to *B,* and then outwards as that taken by the circuit from stimulus light L.

2. *The Reaction Mechanism*—The reaction mechanism consists of that part of the apparatus which records the *responses* given and the presence or absence of the red light which marked the time limit. The current (D. C.) entering at *a,* passes by one branch to the magnet of *C,* the red light tripper, thence to the

left light or right light reaction marker, depending on which reaction key, L or R, is depressed by the subject. From the marker, the pathway is through the 60 watt lights *2* and *3*, thence to the keys indicated and from there outward.

The other branch (D. C) from *a*, passes to *B*, the timer, then through the mercury cup at *t*, which is in series with mercury contact *z*. If the keys are depressed by the subject, the magnet *C* jerks the hook of *C* out of contact with the mercury cup. If the subject does not depress the keys, and thus direct the current through the markers L and R, the current passes on through the red light and to the red light marker, and then outward through light *4*.

By this method, if the circuit is completed by the depression of the key, the appropriate reactions are recorded. If the circuit is not completed in time, the red light flashes and a "slow" reaction is recorded.

3. *Calibration Circuit*—The calibration circuit, represented by dotted lines, is that part used to regulate the time interval between the stimulus light and the red light. In this experiment the time interval used is four hundred sigmas.

For this circuit the current (D.C.) leaves *a* by the same branch as the beginning of the stimulus mechanism and passes to the magnet of tripper *A*. From here it passes to a key, *K*, indicated in the diagram. When this key is depressed the circuit is closed and the tripper arm of *A* releases the arm of *B* and at the same time starts the chronoscope. As soon as the hook at the *t* end of *B* comes into contact with the mercury cup, the chronoscope relay and light *3'* breaks the time recording circuit.

The chronoscope thus measures the time between the passing of the current through the magnet of *A*, which on the stimulus mechanism controls the stimulus lights, and the time of contact at the *t* end of *B*, which in the reaction mechanism controls the red light. That is to say, the chronoscope measures the length of time it requres the hook at *B* to drop from its upper position to contact with the cup.

Lights 1', 2', and 3' are inserted to increase the resistance. By means of a screw device the mercury cup can be adjusted

until the time of fall recorded by the chronoscope is exactly four tenths of a second (400 sigmas). Before each series of experiments the apparatus was calibrated to the desired time interval.

The Record—By means of a roller moved by the motor under the table, a paper feeding device is used which unrolls a record strip before the markers. These markers consist of glass tubes drawn out to a fine point, and then filled with ink. At the contraction of the magnet the attached point is projected against the paper, making a dot. L *stimulus* marker carries blue ink, L *reaction* marker carries red ink, R *stimulus* marker carries blue ink, R *reaction* marker red ink, and Red light marker blue ink. This gives a clear and simple method of recording the exact results of the reactions as well as the stimuli.

The following illustration shows all the possibilities, i.e., all combinations of stimuli and reactions:

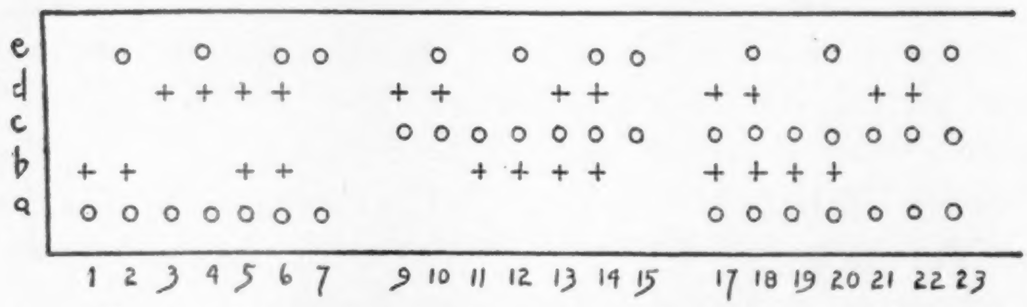


Fig. II.—Specimen record showing all possible reactions.

A dot in column *a* (bottom row) indicates an L light *stimulus*, a dot in column *b* indicates a *reaction* on the L key. A dot in column *c* indicates an R light *stimulus*, one in column *d* a reaction on the R key. A dot in column *e* indicates the flashing of the red light, which means that the reaction has been made more than four tenths of a second after the stimulus.

When a given response in a record was marked 1, it meant that the left light in the dark room had flashed on, and that the subject had pressed down the left hand key in less than four tenths of a second. If however, it was marked 2, it meant that the left light had flashed and that the subject had pressed down the left hand key, but that the time interval had been more than four tenths of a second. Number 3 means that the left light

flashed, but that the subject depressed the right key instead of the left. This method of notation is used throughout in marking records.

By this record system, electrically controlled markers, that are a part of the stimulus and the reaction circuits, make it possible to know in each reaction, what has been the stimulus, what the response and whether the reaction time was greater or less than 400 sigma.

A key to the record is furnished by the following table, in which the numbers refer to the numbers at the bottom of the sample record of Fig. II. For the sake of simplicity the reactions are grouped by omitting numbers 8 and 16.

1.	Left	light	stimulus,	correct response.
2.	"	"	"	, " " , but slow.
3.	"	"	"	, right key response, not left.
4.	"	"	"	, right key response, and slow.
5.	"	"	"	, both keys depressed.
6.	"	"	"	, both keys depressed, slow.
7.	"	"	"	, no reaction.
9.	Right	light	stimulus,	correct response.
10.	"	"	"	, correct response, but slow.
11.	"	"	"	, left key response, not right.
12.	"	"	"	, left key response, slow.
13.	"	"	"	, both keys depressed.
14.	"	"	"	, both keys depressed, slow.
15.	"	"	"	, no reaction.
17.	Both	lights	stimulus,	correct response.
18.	"	"	"	, correct response, but slow.
19.	"	"	"	, left key only.
20.	"	"	"	, left key only, slow.
21.	"	"	"	, right key only.
22.	"	"	"	, left key only, slow.
23.	"	"	"	, no reaction.

By means of the wheel device already explained, the order of the stimuli is varied, but varied in a constant manner so that the subject can not tell what stimulus is to come nor the exact time when it will appear. This eliminates preliminary preparation. A portion of a sample record is shown in Fig. III.

Method of Scoring.—If the correct response is given within the time limit, 400 sigmas, it is counted as perfect. If the correct response is given, but slower than the time limit, it is counted as accurate. Comparisons are made on the basis of

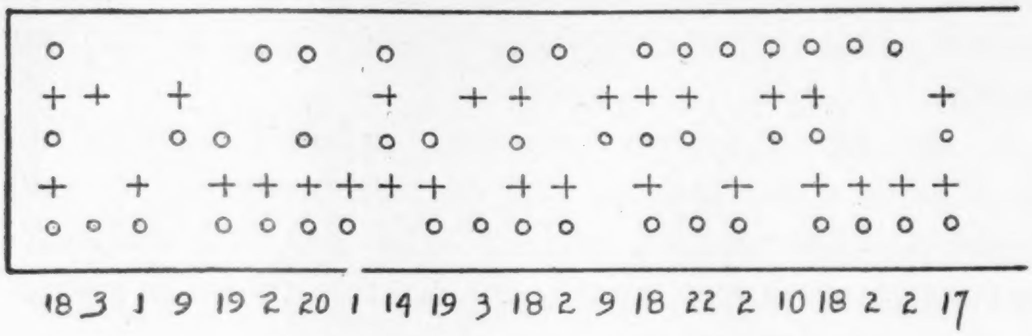


FIG. III.—Portion of sample record.

score, and in all cases scores are converted into percentages. Thus 46 percent perfect reactions means that out of 100 stimuli presented, the subject reacted with 46 perfect scores. This method of scoring is based upon the principle of standard, or "how many fingers reach or pass a set limit."

The first preliminary set was given with the time limit of 300 sigmas, which time was found so fast that very few perfect responses were made by the subjects. The second preliminary set was then given with the time limit of 400 sigmas and showed that the average subjects ranged about 50 percent perfect responses in the trial series. In the final series, one subject who took the experiment with the limit of 400 sigmas, showed a very high percentage of perfect reactions, but when tried out on 300 sigmas, gave too few perfect reactions to give satisfactory results for comparative purposes. One subject, (Go) was given the entire series with the time limit of 300 sigmas. All of these times may seem long, but the reaction is such that it becomes a choice reaction and not a measurement of simple reaction time. This explains the longer time required.

SUBJECTS

Fifteen right-handed subjects were used, eleven women and four men. Eight subjects took all nine series, i.e., all forty-five combinations, and five took two series, i.e., ten combinations. Two others took only one series each and these results were used only in the preliminary study. One subject (Ga) took the entire forty-five combinations twice.

The personnel of the group of eight, that group, the results

of whom have furnished the basis of this report, was as follows:

We. was a professor of psychology at the Ohio State University. He had no piano training, but was an expert mechanician, skilled in the use of hands and fingers for fine adjustments and reactions.

Mu. was a graduate student, doing research work in the department of psychology during the summer session of 1918. She was thoroughly familiar with the apparatus and its use.

Wo. was a student at the University, doing undergraduate work. She was a teacher in the public schools, giving some time to public school music. She played the piano a little, although her training had been on the reed organ more than on the piano.

Mi. was a graduate student, assistant in the department of psychology. She was thoroughly familiar with the apparatus and its use.

Ak. was a student at the University. She was a pianist of considerable ability and also a teacher of piano. She was one of the most practised subjects used.

Go. was a student at the University. He had had no specific training, but his interest in experimental work prompted cooperation as subject.

Ki. was a student at the University, doing undergraduate work. She was a teacher of piano and was interested in the problem for its bearing upon piano technique. She is a pianist of several years training, also a performer on the pipe organ.

Ga. was a graduate student, the writer of the present article. She had studied piano, and violin, had taught piano, and it was her interest in the development of methods of technique that first stimulated interest in this study.

The other subjects used included two instructors in the psychology department during the summer session 1918, Cu. and Ge. The rest were students, with some piano training, two (Si. and Be.) being teachers of piano work as well as performers.

The writer wishes here to express her appreciation of the services rendered by those who gave so cheerfully of their time and effort, and who by their hearty coöperation have made this study possible.

METHOD.

So much confusion has arisen in designating fingers in work of this kind, (particularly where both hands were used) that the following method has been adopted for the present report.

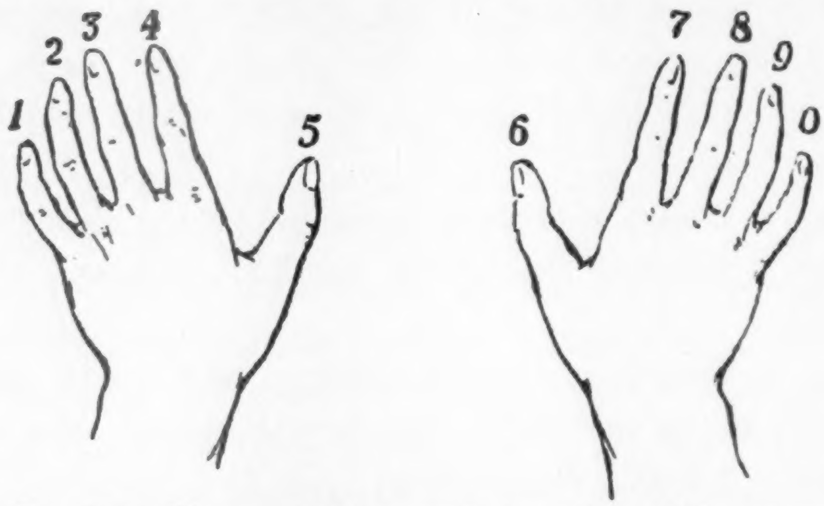


FIG. IV.—Finger notation used throughout this report.

When reference is made to combination 24, for example, the ring finger and the fore finger on the left hand are meant. When reference is made to combination 50, the thumb of the left hand and the little finger of the right hand are meant, and so on for the various combinations. Forty-five combinations are possible, and experimentation was made on the entire number. These forty-five combinations are grouped in sets of five each, making nine sets. Each group of five made up a series. Four subjects took the series in order I to IX and the rest in the order IX to I, but no two subjects had the same order of combinations within a series. The numbers used refer to the diagram and this method of designating the fingers will be used throughout this work.

Each subject was taken into the dark room, in which the keyboard end of the apparatus was located. A single 40 watt tungsten lamp was used to light the dark room, so that the illumination

was about half that ordinarily used in a room. The light was placed behind the subject. The arrangement of stimulus lights and reaction keys is shown in the diagram of Fig. V.

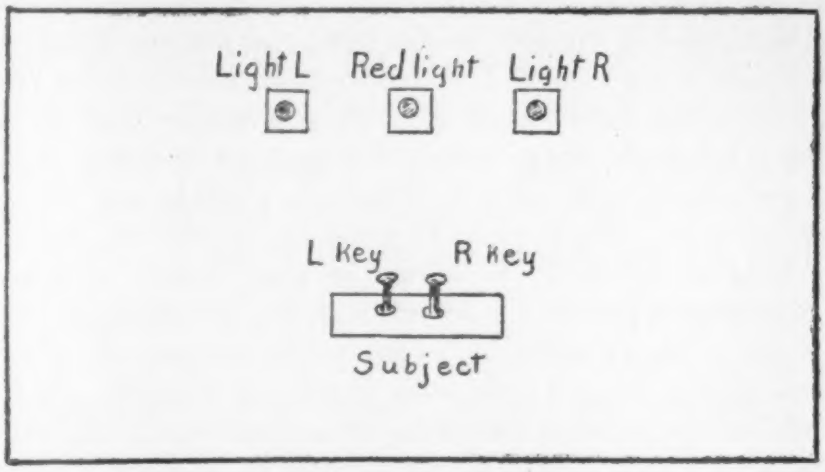


FIG. V.—Diagram of arrangement of lights and keys in the dark room.

The two 10 watt Mazda lights used as stimuli were placed in long wooden boxes with equal sized holes in the ends, so that the subject saw not the glare of the filaments of the bulb, but rather the glow of the yellow light that filled the box. The placement of the red light was in a similar box. The keys with which the subject reacted were of the depression key type, ordinarily used, but so arranged, by the tension of the spring that it required 70 grams weight to depress each key. The amount of weight required to depress the keys of pianos of different makes varies somewhat, but the variation among the keys of any given piano of good quality is small. A Knabe grand piano which was tested required a weight of 53 grams to depress the keys. Only a few keys varied from this amount and none by more than six grams. Likewise a Chickering grand piano which was tested required a weight of 37 grams to depress the keys, and showed no variation greater than 7 grams. The keys used in this experiment requiring 70 grams weight have enough resistance to equal that of any of the pianos of so-called stiffer action and yet is not equal to the amount usually given by all the subjects in reacting to keys of this sort. In other words, the resistance was not enough to cause errors due to failure to depress the keys far enough to make electrical contact. Whenever the finger reacted to the key, it was recorded.

The following instructions were given to each subject at the beginning of the first series:

You are to sit in here thus: (experimenter takes place in the chair, places hand on the keyboard and demonstrates). Now in the box on the left there is a yellow light, and in the box on the right there is a yellow light. When the light comes on in the left-hand box, press down the left-hand key as quickly as possible; when the light comes on in the right-hand box, press down the right-hand key as quickly as possible. When the two lights come on at the same time, press down both keys as quickly as possible and as nearly at the same time as you can. Try to avoid tripping, i.e., putting one key down before the other. Now in the middle box there is a red light. This will come on when the responses which you have made to the yellow light have been too slow. You are to try to make the responses as accurate as possible and at the same time to keep the red light from flashing in as many cases as you can. In each set you are to use a different pair of fingers; I shall indicate which finger combinations to use, just before each series is begun.

After the first series it was unnecessary to repeat the instructions. Merely a reminder of the stimuli, the responses required and a naming of the fingers to be used were given. A rest of 60 seconds was allowed between combinations, and the first six or eight reactions were not counted. Each series, i.e., each set of five combinations, was given at a separate time, usually on succeeding days. A single series required forty minutes for execution.

Results

Difference between fingers on the basis of speed.—A comparison of the relative speed of the fingers is shown in Table I, which gives the rank of each finger for each individual.

Table I.
Rank of Individual Fingers on Basis of Speed.

Subjects	We	Wo	Mu	Ga	Mi	Ak	Go	Av. Rank	A.D.
Finger 1	10	7	6	8	8	10	10	8.4	1.3
2	5	10	10	5.5	9	3	4	6.6	2.6
3	8	9	4	10	4	7	7	7.0	1.7
4	7	8	9	1	7	4	5.5	5.9	2.0
5	9	6	8	4	10	8	2	6.7	2.3
6	2	3	5	2	1	5	5.5	3.3	1.5
7	4	4	3	9	3	2	1	3.7	1.6
8	6	5	2	7	6	1	8	5.0	2.0
9	3	2	7	5.5	5	6	3	4.5	1.5
0	1	1	1	3	2	9	9	3.5	2.9

Correlations on the basis of the relative rank between the several fingers when used by the different subjects does not give high correlation except in a few cases. This only means that individuals differ among themselves as to the relative skill of the fingers. It is however noticeable that certain fingers are usually the best fingers, the variation being greatest among the rest of the fingers. The number of right hand fingers placed in the upper 50 percent of the ranking is as follows: We, 4; Wo, 5; Mu, 4; Ga, 3; Mi, 4; Ak, 3; Go, 3. The same numbers are accordingly found for the left hand fingers in the lower 50 percent of the ranking. The subjects that show the greatest speed also show greater distribution of the fingers of the two hands, e.g., Ga., Ak., and Go.; and the subject that was the slowest throughout, Wo., shows the greatest grouping, all five fingers of her right hand being in the upper 50 percent of ranking.

Comparison of Right Hand with Left Hand Fingers.—In agreement with the findings of Kiesow, the present results show differences not only between hands, but also between the fingers of the two hands. These differences are best shown by Table II. The results are given in terms of percent, which value is derived by taking the sum of all the perfect reactions for a given finger in combination with each other finger and dividing the result by 450. The differences between right and left hands as shown here are based on 2,250 reactions for each hand.

TABLE II.

Differences between Fingers on Basis of Speed.

Subj.	Left Hand						Right Hand						Diff.
	1	2	3	4	5	Av.	6	7	8	9	0	Av.	
We	51	58	55	56	53	54	66	62	57	62	66	62	8
Wo	18	14	16	18	19	17	40	36	29	44	46	40	22
Mu	53	46	56	47	49	50	56	57	61	56	65	59	9
Ga	40	42	37	50	42	42	48	39	40	42	44	42	0
Mi	53	51	56	53	50	52	64	57	53	54	60	58	6
Ak	70	81	77	80	77	77	79	84	86	78	71	80	3
Go*	18	28	28	28	29	26	28	37	27	29	26	30	4

* The figures for Go. are the basis of a shorter time, 300 sigmas, but the differences between fingers and between hands is shown just as clearly.

The results show that the right hand excels with respect to speed in every case except one, subject Ga. Ga was a subject whose mother was natively left-handed, but who had acquired right hand habits through training. Ga's father was a member of a family that showed decided tendencies toward ambidexterity. One brother of Ga is left-handed. Moreover the training of the subject Ga has been such as to develop the reactions of the left hand. Piano practise, typewriting and other performances using the fingers of the left hand were habitual. In addition to this there is the factor which Kiesow mentions with regard to the development of the fingers of his own left hand, particularly the little finger, namely that the subject had in earlier years played the violin, which performance develops the reactions of the left hand fingers, especially the little finger.

It is again noticeable that the subject that showed the slowest reactions was the subject who showed the greatest differences between hands. (Wo., difference of 22). Likewise Mu, whose training next to Wo's was least complete showed a great difference between the performance of the two hands (10). It seems probable that as the practises which increase finger efficiency go on, the differences between the fingers and between the two hands grow less and less. *In other words, instead of resulting in a uniform increase with each finger, practice tends to equalize the reactions of the several fingers.*

With regard to accuracy, differences between fingers and between the two hands are again evident, but are much smaller than the differences in speed. The values are obtained by taking the sum of all the correct reactions, whether on time or slow, and dividing by 450 as in the preceding table of results. The differences in accuracy for the ten fingers are shown in Table III.

The differences here between the two hands are too small to have much significance. The fact that the percentages are so large throughout indicates that the method is not a sufficiently fine measure of accuracy. But it has the advantage of measuring this factor at the same time as the speed, i.e., in the same performance. The right hand is more accurate than the left except

TABLE III.
Differences between fingers on Basis of Accuracy.

Subj.	Left Hand						Right Hand						Diff.
	1	2	3	4	5	Av.	6	7	8	9	0	Av.	
We	81	85	86	80	87	84	90	86	86	88	86	87	3
Wo	89	89	89	88	88	88	93	90	89	90	88	90	2
Mu	89	91	91	90	76	87	86	87	92	87	89	88	1
Ga	92	93	93	94	95	93	93	95	94	93	93	93	0
Mi	80	84	86	83	79	82	86	86	85	83	84	85	3
Ak	91	94	94	92	93	92	95	95	96	95	89	94	2
Go	75	78	84	79	78	79	76	75	80	74	66	74	—5

in one case, subject Go. Subject Ga., as in the measurement of speed, shows no difference between the right and left hands.

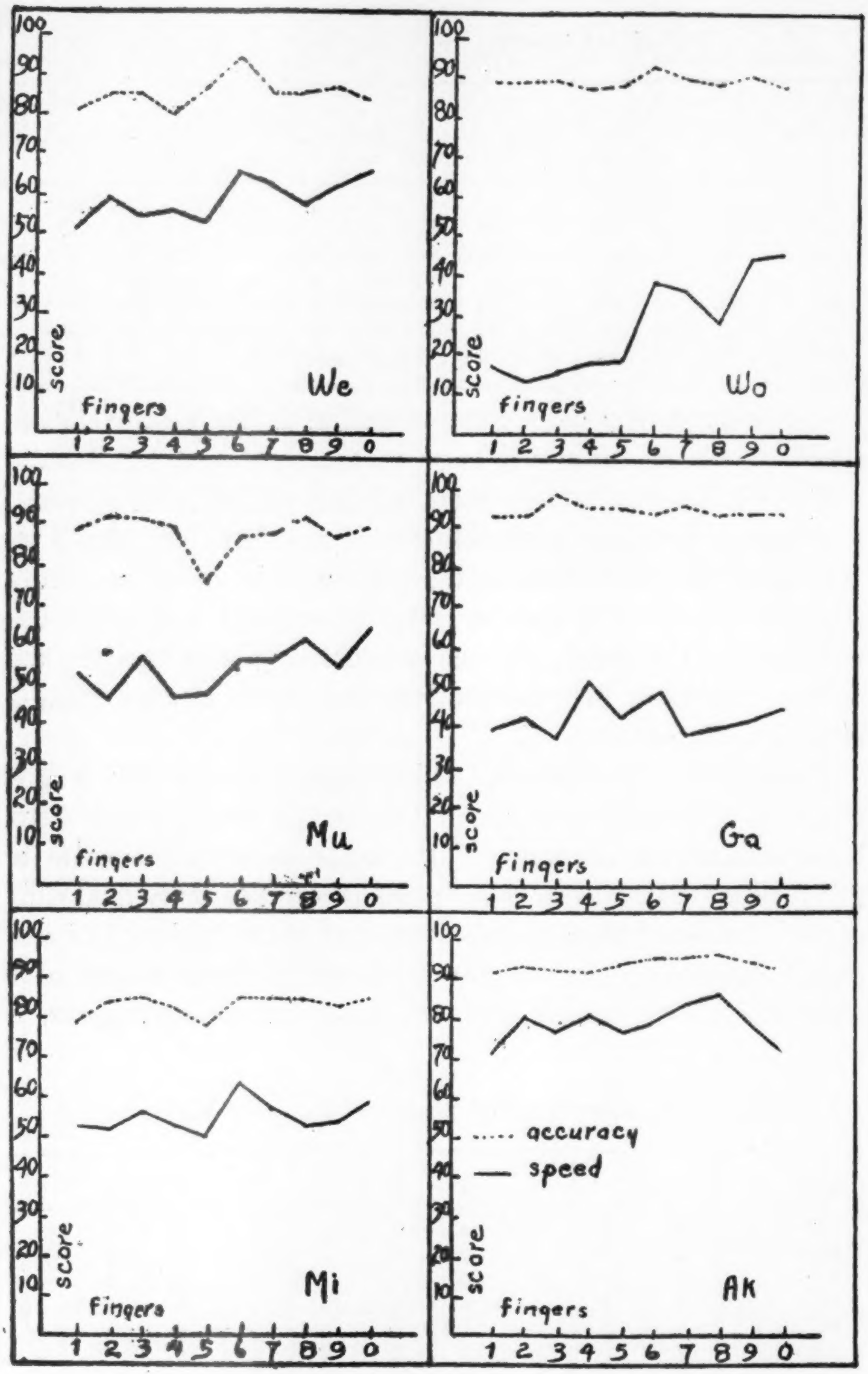
The explanation offered there applies equally with respect to accuracy. A similar explanation might perhaps be offered with regard to Go, who showed the left hand to be more accurate than the right. His mother was left-handed and some other members of the family showed unusual skill with the left hand.

The differences between the fingers in speed and accuracy are shown in Graph I.

Fingers in Combination.—The finger with which a given finger is combined is a factor influencing the speed and to a lesser extent the accuracy of the response of a finger at any given time. Here as in other points there are individual differences. However there is indication that in the majority of cases, certain fingers are more easily combined with the thumb of the right hand for example than the other remaining fingers, etc.

TABLE IV.
Finger with which a given finger produces the highest speed.

Subject	1	2	3	4	5	6	7	8	9	0
We	0	7	9	0	9	4	2	6	1	1
Mu	0	7	7	0	8	8	2	6	5	1,4
Wo	6	7	9	6	0	4	9	5,6	7	4
Ga	0	7	9	0	9	1	2	6	5	1,4
Mi	3	6	9	1,7	8	1,4	3	9	3	5
Ak	8	7	6	9	8	4	3	2	1	2
Go	8	0	0	7	0	0	8	7	7	5



GRAPH I.—Differences between fingers in speed and accuracy.

TABLE V.

Finger with which a given finger produces the greatest accuracy.

Subject	1	2	3	4	5	6	7	8	9	0
We	3,7,0	6,7	1	1	7	2,4	2	2	1	1
Mu	6	7	5	6	7,8	8	6,9	7,8	8	6,7
Wo	1	4	8,9	2,6	4,7	2,4,0	0	3,5	0	5
Ga	7	5	1	7	1,2,4	3	5	3,4,6	2,6,7	1,6,8
Mi	7,8	1	7	7,0	8	0	3	4	0	1,2,5
Ak	7	7	6	0	6	5	2	9	1,9	1,4
Go	9	8	0	1,9	3,0	3,4	8	9	1,6	5,6

For three of the subjects, finger 1 obtains its greatest speed in combination with finger 0, for two others when with finger 8. Five of the seven subjects obtained the greatest speed with finger 2 when in combination with finger 7. It is not necessary to call special attention to the values for each finger as this can be derived from the table. The general conclusion to be drawn is the fact that the greatest speed is obtained when the given finger is *acting with a finger of the opposite hand.* For fingers 1, 4 and 6, six of the seven subjects show this to be true; for fingers 2, 3, 5, and 0, all seven subjects agree; and for fingers 7 and 9 five of the subjects find the greatest speed when the combination includes a finger of the opposite hand. Finger 8 offers a decided exception in that all but one subject produced the greatest speed with this finger when it was in combination with some other finger of the same hand (right hand). It is quite possible that the middle finger of the right hand has by continued use become more independent in its movements than the other fingers, and has developed skill in operation with the fingers of the same hand particularly. In grasping an object, manipulation of tools and other articles, the middle finger and the thumb are continually juxtaposed. Four of the subjects found that the greatest speed was obtained when finger 8 was in combination with finger 6, which represents the thumb of the right hand, one when in combination with the index and another when in combination with the ring finger.

There is little similarity among the subjects on the basis of accuracy (Table V). A much wider variety of combinations is

recorded. The same general principle holds true, however, as in the case of speed, i.e., the greatest accuracy is obtained by most observers when the finger used with the given finger is on the opposite hand.

Comparison of Two-Finger with One-Finger Reactions.—Although responding to stimuli with two fingers requires more movement, and also the excitation of more pathways, nevertheless the results show that two-finger reactions are the faster as well as the more accurate. The method of derivation is: the sum of the 1's plus the 9's for the entire 45 combinations, divided by 4500 equals the percent of perfect scores for all single finger reactions involved; the sum of all 17's for the entire 45 combinations, divided by 2250 equals the percent of perfect scores for all double-finger reactions involved. The results are as follows:

TABLE VI.

Speed of Single-finger Reactions Compared with Two-finger Reactions.

Subjects	Single-finger	Double-finger
We	59	74
Wo	28	46
Mu	54	76
Ga	43	68
Mi	55	74
Ak	78	89
Go	28	41

TABLE VII.

Accuracy of Single-finger Reactions Compared with Two-finger Reactions.

Subjects	Single-finger	Double-finger
We	85	97
Wo	89	98
Mu	87	97
Ga	93	97
Mi	83	99
Ak	93	99+
Go	76	99+

With the score for one-finger reactions based on the results of 4500 single reactions, and the score for the two-finger reactions based on the results of 2250 reactions a considerable degree of reliability may be assumed. Cattell claimed that the variable error is practically eliminated in the average of 100 measurements for each. For every subject the two-finger re-

actions are much the faster, and are also more accurate. This might be explained in several ways: (1) increased stimulation, (2) nervous accumulation, (3) absence of the choice element.

Todd[28] found that whenever another stimulus was added to a given stimulus, there was a reduction in the reaction time. "That is to say, the added stimulus facilitated or reënforced the reaction-reflex." On this ground, it is reduced to the assumption that strong stimuli force the barrier across the synapses more quickly than do weak ones. However in the present work, whenever a double stimulus is given, a double reaction is also required. It would be difficult to determine how much of the speed gained in the two-finger reactions were due to increased stimulus, apart from other factors involved.

When the fingers are not reacting, both are in preparation for the coming stimulus, inasmuch as the subject has no means of knowing which stimulus will be presented next. If the stimulus that appears is a single one and for the right-hand finger, the other finger must be inhibited or kept from reacting. This is just as much a part of the process as the movement downwards of the approximate finger. Now, when a double stimulus appears, requiring the movement of both fingers, this element of choice and inhibition is lacking. The "set" prepared in both "releases the trigger" and the double movement occurs. This is one of the elements in the shortening of the time.

The instances in which only one finger responds to a double stimulus are very much rarer than those in which two fingers respond to a single stimulus. In those cases where there were two lights and only one finger reacted, it was more often the right finger than the left. This was true for five of the seven subjects. In those cases where only one stimulus light was given and two fingers reacted, the results are as follows:

With five of the seven subjects more errors of this kind occur when the right hand stimulus is given. In other words, the left hand makes more uncalled for reactions than does the right. This means poorer inhibition of the movements of the left hand, inasmuch as the "set" is opened for either reaction when the

[28] Todd, J. W., "Reaction to Multiple Stimuli," Arch. of Psych., v. 25, 1912.

TABLE VIII.
Double reactions to single stimuli

Subjects	Left stimulus both fingers reacting	Right stimulus both fingers reacting
We	18	13
Wo	9	10
Mu	9	14
Ga	6	6
Mi	16	17
Ak	5	7
Go	22	25

stimulus appears. This is another evidence of the less efficient control of the movements of the left hand as compared with the right. These figures represent the results of 2250 reactions converted into percentage on the basis of the whole.

Relative Efficiency of Combinations.—In another connection it was noted that the combination which is most efficient for different individuals may vary, but that is usually a combination involving one finger on each hand. Further examination of the relative score of the different combinations used shows that the individuals differ greatly as to the order of efficiency, both in speed and accuracy. The scores for each combination of fingers and for each subject when compared bear out this fact.

Correlation of the relative rank of the combinations for different individuals show for the most part low and in some cases negligible correlations. A few are high enough to be significant. This marked difference between individuals on the basis of combinations is probably due in large measure to a difference in training. When the fingers are considered apart from any particular combination, certain fingers seem always to excel, i.e., the same finger is found to be best for several individuals, and yet their most efficient combinations of fingers vary. No two people perform exactly the same acts or movements in ordinary life. The fundamental movements are similar and accordingly certain fingers excel in speed and accuracy. Moreover, certain combinations are higly developed in all subjects. For example, combinations 16, 10, 27, 40, 70, 39 and others occupy a relatively high rank with most subjects, while combinations 25, 15, 23, 29, 35, 45, 49 and others occupy

a low rank with most of the subjects. These are the most highly developed and the lowest developed combinations. The lack of correlation between subjects on the basis of the whole forty-five combinations, is brought about by the wide variation in the rank of other less used combinations of fingers, which vary from subject to subject in degree of development.

The five subjects who took only ten finger-combinations, were given combinations of such a nature that they would include 4 right hand combinations, 4 left hand combinations and 2 two hand combinations. Although the figures are smaller here in the case of the first group of subjects, the results are worthy of mention. An average of the results of the several combinations and for the five subjects gives the following:

Combination	Speed	Accuracy
Left hand	60	90
Both hands	59	94
Right hand	44	92

The combination which were presented to these five subjects were simply selected as being those frequently used in piano, work, so that it is a mere element of chance so far as this experiment is concerned. When the relative rank of these individual finger combinations is noted in the records of those subjects who performed all forty-five sets, the above results are found to be in harmony. In other words, it so happened that the combinations chosen were right hand combinations which ranked low comparatively, and left hand combinations which ranked high. This merely shows then that there is a fair degree of reliability in the method even where only a few sets are required of each subject. It also demonstrates the importance of indicating the members of the body used in any given experiment. On the basis of one combination of fingers very different results are obtained from those using some other combinations and may lead to erroneous conclusions.

Some practise effect may be included in the score of the combinations that occur later in the series of forty-five combinations. This will effect to some small degree the relation of combinations, but in the total results this effect tends to be counter-

balanced by the inverted order of presentation of the series to different subjects. Moreover, the order of combinations was so aranged that in almost every group of five, each finger was used once. There was a few modifications from this arrangement, but not variation enough to give one finger more practise than another. By this means, even though in the later series the fingers may have a slight increase in speed due to practise effects, it is uniform, so that in averaging results, this factor is alike for each finger.

Considering the twenty combinations which rank at the upper end of the scale for each individual, it is found that by far the majority of these combinations are combinations using one finger on each hand. For We and Ak, 16 of the 20 combinations are two-hand ones, for Wo, Mu, Ga and Mi, 13 of the 20 are two-hand combinations and for Go 12. Most of the remaining combinations that rank among the twenty fastest are right hand combinations, i.e., both fingers belong to the right hand. Only nine combinations out of the whole 140 (seven subjects with 20 combinations each) are left-hand combinations. It seems conclusive therefore, that *two-hand combinations are fastest, right-hand combinations next and the left-hand combinations the slowest.*

Another question involved in the general problem of combinations is whether the speed of *two-finger* reactions is greater when the two fingers are on the same hand or on two hands. In our discussion of the fastest combinations, both single and double reactions are considered in the total score. The problem with which we are now concerned deals with *double* reactions only. By converting into percentages all the double reactions (represented in the record sheets by number 17's) and then segregating into three groups, namely two-hand, left-hand and right-hand, a comparison may be made according to Table IX.

For all the subjects except We, double reactions which involve left hand fingers only, are the slowest. For four of the seven subjects, two-finger reactions involving two hands are the fastest and for the remaining three the right hand two-finger reactions are the fastest. Féré[29] concluded that the reaction

[29] Féré, Ch., Op. cit., reference footnote 14.

times for the two hands acting together was greater than either hand acting alone. In no case do the present results agree with this conclusion. On the contrary, reactions with the two hands acting together are faster than the left hand acting alone, and in the majority of cases faster than the right hand acting alone.

TABLE IX.
Two-finger reactions on a basis of hands.

Subject	Both hands	Left hand	Right hand
We	82	70	61
Wo	50	27	53
Mu	76	74	80
Ga	74	55	65
Mi	78	62	74
Ak	92	83	89
Go	44	22	50

Symmetrical Movements.—It would seem on first consideration that not only should two-hand movements be faster, but that also those two-hand movements which are symmetrical should be the faster. In the ranking of the combinations in the order of speed, the symmetrical combinations, i.e., combinations 10, 29, 38, 47, and 56, do not occur frequently enough to justify the assumption that the symmetry plays any role. In the fastest twenty combinations, combination 10 appears for four subjects, 29 for none, 38 for three, 47 for one, and 56 for four. Out of a possible thirty-five times in the records of the seven subjects, symmetrical combinations appear but twelve times and in such cases as they do occur, it seems to be a matter of more efficient finger rather than the symmetrical two-hand movement.

If the double reactions alone are considered, the average of the 17's for the five symmetrical combinations is considerably less than the average of all two-hand double reactions. For five of the seven subjects and for one of the two remaining subjects the values are exactly the same. There seems to be no reason for concluding that symmetrical movements are faster than those two-finger movements that are not symmetrical, although two-finger movements when the fingers are on opposite hands are faster than two-finger movements when the fingers are on the same hand.

Premature Reactions.—Very little attention need be paid here to responses that preceded the stimulus. In the first place the element of anticipation was practically eliminated by means of the irregular order of presentation and time interval between stimuli. The number of premature responses in these experiments was so small that they were discarded. There were only 12 or 15, and these were found chiefly in the records of one subject.

Woodworth[30] points out that if the stimulus follows at an irregular interval, the reaction is not so short as when the procedure is regular. "If, indeed, the procedure is so regular that the movement of the stimulus can be exactly anticipated, the movement may be made to coincide with the stimulus in time, and the whole character or the experiment thus changed. This result is avoided by varying the preliminary interval within narrow limits." When in addition to the irregular time of the presentation of the stimuli, the order is varied, the subject cannot prepare a preliminary "set" for any one reaction. This setting up or opening up of a particular pathway which gives the impulse a quick passage to the motor nerves, as Woodworth describes it, is not wholly possible. Both fingers must be ready to react as quickly as possible. The difficulty often lies in inhibiting the action in the finger not called upon by the stimulus presented. One subject Ga., after taking 50 or more sets was able to anticipate the order of the stimuli. This subject, however, felt that it was no particular advantage, but rather made the performance more complex than the simple response after the stimulus was given, without knowledge of what it was to be. The fact that the subject could anticipate the order after many series had been performed did not influence the results and conclusions derived, from the experiment, for not until after the whole of the 45 combinations had been taken could this subject even anticipate any of the orders.

Effect of Practise.—The question as to the effect of the repetition of the experiment on the later combinations, in other words

[30] Ladd and Woodworth, "Physiological Psychology," New York, 1911, page 481.

the effect of practise, was studied. It might seem that those finger combinations which occurred later in the series have an advantage by this fact, due to the practise acquired by performing the experiment with other finger combinations. The order of presentation of the combinations was such that in the first half of the total number of trials, there were used approximately the same number of right hand combinations as left hand combinations, and about twice as many two-hand combinations. This means that there is a balanced distribution of the combinations, so that the greater speed of the right hand combinations over the left, or the greater speed of the fingers of the right hand over those of the left, cannot be attributed to this factor of practise. In addition four of the subjects were given the combinations in the reverse order from the original four subjects.

A study in practise effect was carried out by means of a repetition of the entire 45 combinations by one subject Ga., after a period of a few days rest. The result was that in both speed and accuracy trial II give an increase over trial I. Table X shows the relative values according to fingers, for the two trials.

TABLE X.

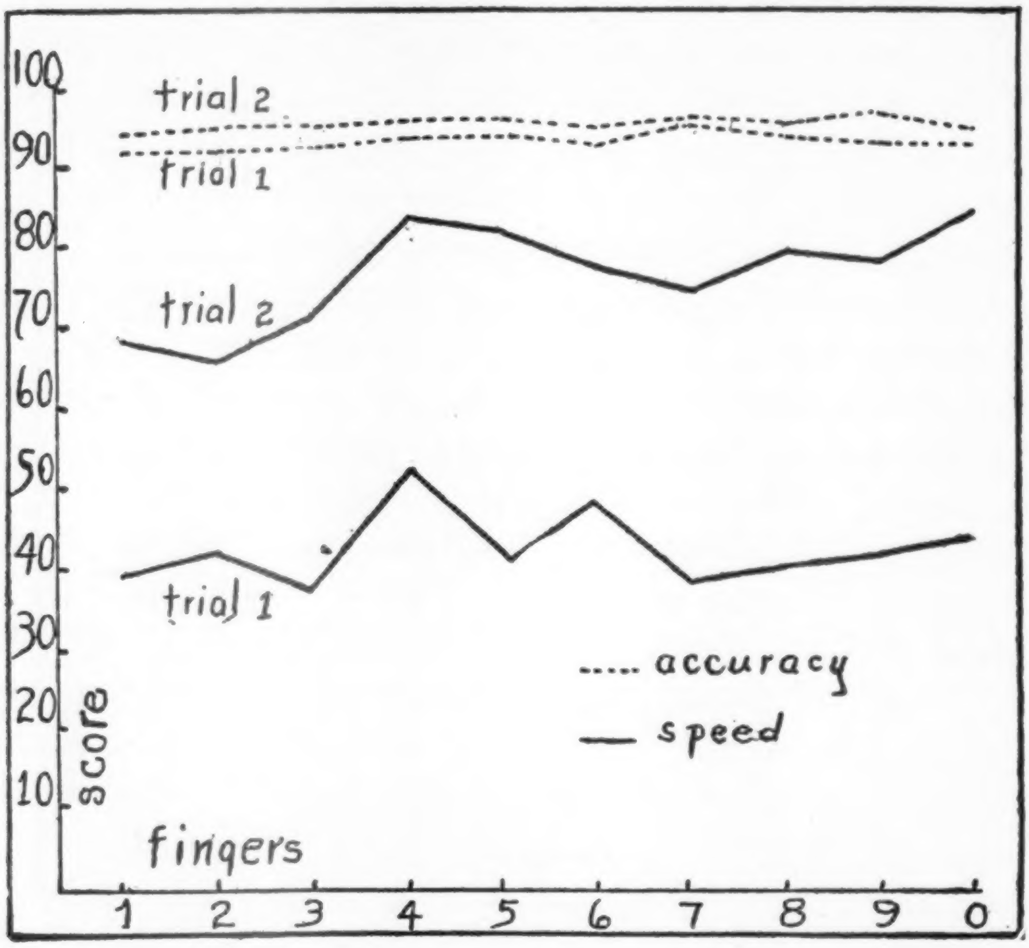
Trials I and II for subject Ga. (Trial II made after a few days of rest)

Finger	Speed		Accuracy	
	Trial I	Trial II	Trial I	Trial II
1	40	68	92	94
2	42	66	92	95
3	37	72	93	95
4	53	84	94	96
5	42	82	95	96
6	48	78	93	95
7	39	75	95	96
8	40	80	94	95
9	42	79	93	97
0	44	85	93	95

For each finger there is a decided increase after the period of rest. The increase in speed is extremely high. The increase in accuracy is very small, but the fact that there is an increase in each finger when the values representing each finger are derived from averaging 1350 reactions, makes them at least significant. This increase may be in part explicable in terms of

the rest period, the so-called "setting" of the habits formed. It is exactly comparable to that which we find in the case of typewriting, telegraphy and other forms of learning experiments. Cattell also concluded that after an interval of some duration (three months) during which no reactions were made, his subjects' times became in general shorter, markedly so in the case of choice reactions.

The more significant facts brought out by the data obtained by the second trial of Ga. are shown upon examination of Graph II. In both trials there are individual finger differences



GRAPH II.—Practise effects. (On basis of repetition of entire series).

and the general shape of the graph is the same for both trials. The increase is a little more in the case of some fingers than in others, however. The similiarity on the basis of accuracy is even more striking. The amount of practise effect may vary with the respective fingers. It is not the purpose of this work to investigate that point, but it is likely that the muscular and

nervous structure of the separate fingers is such that one finger will not require the same amount of practice as another in order to obtain a uniform increase in excellency (speed and accuracy). This particular case does not show the marked difference between fingers in either trial, but this was characteristic of the results of Ga's work throughout. As was mentioned earlier, Ga's training had been such as to reduce the difference between fingers which inherently exists, and in addition was a member of a family in which there were several left-handed members and others who showed a tendency towards ambidexterity.

Individual Differences.—Not only between the fingers of a given individual do we find differences, but also in the total speed or accuracy that individuals may attain regardless of the fingers used. These results are best shown in Table XI and Table XII.

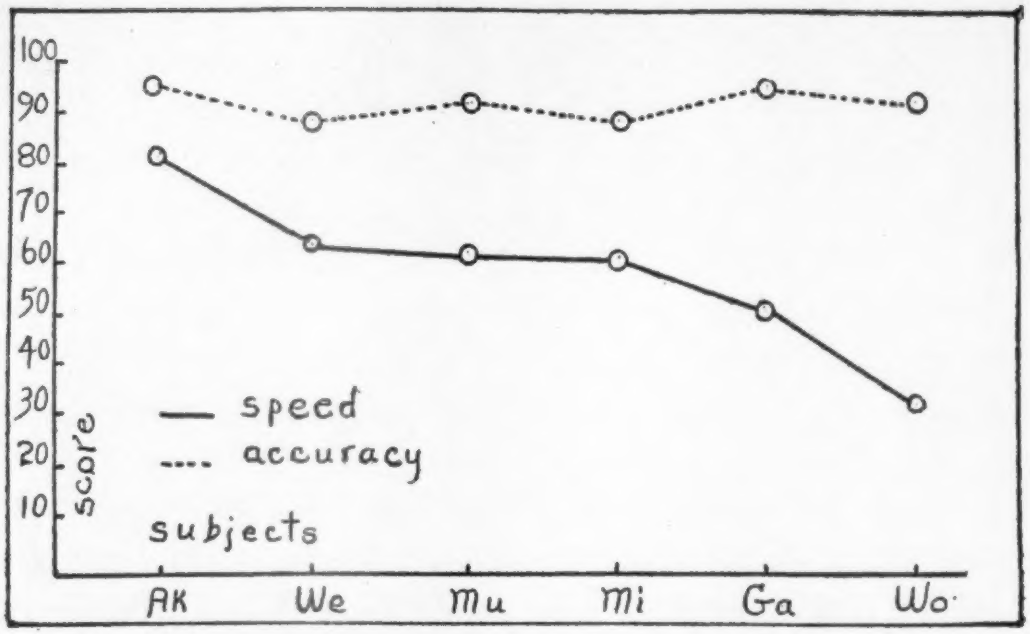
TABLE XI.
Differences between Individuals
(Speed)

Subject	Highest percent attained	Lowest percent attained	Average of all 6750 reactions
We	94 (27)	13 (35)	64
Wo	81 (79)	9 (78)	33
Mu	98 (68)	17 (29)	62
Ga	87 (40)	25 (35, 78)	51
Mi	87 (50)	28 (35)	61
Ak	96 (58)	53 (45)	82

TABLE XII.
Difference between Individuals
(Accuracy)

Subject	Highest percent attained	Lowest percent attained	Average of all 6750 reactions
We	96 (26)	73 (45)	89
Wo	99 (46)	83 (48)	92
Mu	99 (28, 68, 89)	61 (45)	91
Ga	99 (60)	90 (12)	95
Mi	95 (37, 39, 60)	77 (45)	89
Ak	100 (56)	87 (45)	96

The number in parenthesis indicates the finger combination used when the given score was attained.



GRAPH III.—Individual Differences in Total Achievement.

In addition to the preceding records there are the records for subject Go. Go was given the first fifteen combinations with the time set at 400 sigmas. Practically no slow responses were recorded, so that an entire new series was begun, leaving the 15 that had been performed previously, until the last of the set of forty-five combinations. The time used for this series was 300 sigmas. This meant that his average reaction time was enough faster than 400 sigmas to allow even the slower reactions to come above the 400-sigma limit. The records taken from the 300-sigma series show the following:

	Speed	Accuracy
Highest percent attained	72 (47)	93 (19)
Lowest percent attained	7 (14)	63 (90)
Average of all 6750 reactions	31	84

Numbers in parentheses indicate finger combinations.

It is certain that Go. was the fastest of the seven subjects here compared. It is also likely that his reactions are the most accurate, although there is no direct method of comparison. However, 92.6% accuracy with a 300-sigma time limit, is perhaps a better result than those higher figures with the 400-sigma time limit. It does not follow, however, that the person who is the fastest, is also the most accurate. On the basis of the six subjects whose conditions are the same, the fastest sub-

ject, Ak, is also the most accurate, but a correlation of the relative positions of the six subjects in speed and accuracy gives a correlation of but .09. Within certain limits the opposite is true. The more time taken in making the responses the more accurate they are likely to be.

There is a considerable difference between individuals in respect to the amount of variation from one combination to another. In speed, the variation ranges from 43 (subject Ak) to 81 (subjects We and Mu). By this is meant the difference between the lowest and highest speeds for the subjects indicated. In accuracy the variation or range is from 9 (subject Ga) to 38 (subject Mu). With one exception, the highest speed was obtained when using the two hands, i.e., one finger on the left hand and one on the right hand. The lowest speed was obtained by three subjects when using the combination 35, and by another when using the combination 45, both of which are left hand combinations involving the thumb. Likewise the greatest accuracy was obtained in every case when a combination involving both hands or two fingers on the right hand was used. The lowest accuracy was attained with the combination 45 by four of the six subjects and with combination 12 by another.

The difference between individuals can best be explained on the basis of the individual differences in reaction tme. This is due in part to individual differences in anatomical and nervous structure. Evidence here is chiefly theoretical and by analogy, but the number of fibres in various muscles involved varies somewhat from individual to individual. Moreover the training of each subject has been unique. The daily practises of no two individuals are exactly alike. Consequently each has developed certain muscles, as well as certain pathways, for his own individual responses.

This fact is evident in a comparison of the results of those subjects whom we might designate as trained and those untrained. Ga and Ak are the two pianists of the group and their results show that the fingers of the practised individuals tend to become more nearly uniform in both speed and accuracy. There is less range of score on the basis of fingers. (Table II and

Table III). There is less difference between hands and between fingers. We hear much talk among teachers of piano technique about developing the speed of the two hands to the same interval, particularly in the two-finger and two-hand movements used in chords. Nevertheless, there has been but slight development of exercises directed toward strengthening the lagging fingers. Little has been known of the actual finger differences, and methods of technique have not been advanced from this angle.

Conclusions

Briefly stated, the results of these experiments, which include some 70,000 reactions, under as uniform conditions as possible, justify the following conclusions:

1. There are measurable differences between the reactions of the several fingers, first on the basis of speed and second on the basis of accuracy.

2. The fingers of the right hand (at least in right-handed people) are on the average faster than the fingers of the left hand. The fingers of the right hand also excel in accuracy, but the differences in this respect are slight.

3. The finger with which a given finger reacts effects the speed of the given finger. In other words, finger 2, for example, reacts faster when the other finger of the combination is finger 7, than with any other finger. The effect of the combination upon the reaction time of the given finger is relatively uniform for the different subjects. Anatomical structure and common developments due to habits of life are probable explanations for this similarity.

4. Two-finger reactions, at least where there is double stimulation and double reaction, are faster than single-finger reactions, and are also more accurate.

5. Two-hand combinations, i.e., those in which one finger is on the left hand and the other on the right, give faster reaction times than those combinations in which both fingers are on the same hand. Of the twenty combinations, (out of the whole

forty-five) that are the fastest in reaction time, 68 percent of them are two-hand combinations, 26 percent are right-hand combinations, while only 6 percent are left-hand combinations. In opposition to the assertion of Féré, these results justify the conclusion that two-hand reactions are the fastest, right-hand reactions second and left-hand reactions slowest of all, when double reactions are concerned.

6. Practise increases the speed and accuracy of all the fingers. It tends to increase some more than others, thus lessening the difference between fingers. However, after a second performance of the entire forty-five combinations, finger dfferences are still found, *similar* to those originally present.

7. Individuals differ, both in speed and accuracy. There are some individuals who, with unlimited practise will not attain the speed and accuracy which some others show at the initial trial. With very few exceptions, subjects agree that greatest speed is obtained when using two hands, i.e., one finger on each, and the lowest speed is obtained when both fingers used are members of the left hand. The same is true for accuracy. Trained subjects, those having a considerable amount of piano or other similar practise, show less difference between fingers than do the untrained subjects.